Nanomechanical Chemical Sensor Platform

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***Abstract*— For a gas phase chemical sensing, we have developed a selective, sensitive and portable sensing platform, which integrates bio receptors, chemo-mechanical sensor array, and electrical readout circuits. The biggest challenge in chemical sensors is selectivity of a receptor to its respective target molecule against a background of various interfering agents. For target specific receptors, sequence-specific recognition motifs have been identified through direct evolution methods, called phage display. We have demonstrated and updated a parylene micromembrane surface stress sensor array which uses capacitive signal readout. For a fully integrated sensor platform, a portable chemical sensing board has been built.**

Keywords-Chemical sensing; selectivity, sensitivity; bio receptors; micromembrane

I. INTRODUCTION

Chemo-mechanical transducers such as a cantilever beam can detect surface stresses created by ligand-receptor binding at very low concentration with sufficiently high signal-to-noise ratio [1, 2]. Such a high sensitivity opens many applications such as detection of explosives and chemical warfare agents, as well as environmental contaminants, which can have very low vapor pressures. The biggest challenge in chemical sensors is selectivity of a receptor to its respective target molecule against a background of various interfering agents. A fundamental lesson that we learn from biology is that, for molecular recognition, multiple binding sites should exist for a target molecule. This provides sufficiently high free energy change for a specific molecule making it highly selective. Inspired by the biological process, we can identify the specific recognition motifs. We have previously reported on major progress in this area with regards to the development of a 2-D multiplexed cantilever array platform for high-throughput chemical sensing and analysis [3], as well as the development of a novel parylene micromembrane surface stress sensor array using capacitive signal readout [4]. Here, we discuss a target-specific bio-receptor search, a parylene micromembrane sensor, and system integration.

II. TARGET SPECIFIC BIO RECEPTOR

Target specific receptor screening for dinitrotoluene (DNT), which is the decomposition product of trinitrotoluene (TNT), was carried out using the phage display process. This screening method, depicted in Fig 1, was utilized for the identification of DNT binding peptide receptors. The process utilizes a large combinatorial library of M-13 bacteriophage expressing candidate receptors on the pIII region of their protein coat. This receptor library was comprised of variable regions 12 amino acid in length. The library of potential receptor-bearing phage was then allowed to incubate with the target molecule, such as DNT, at room temperature for 30 minutes. The non-specific binders are washed away with a buffer containing 0.1% Tween, a detergent. Specifically bound phage are eluted and captured from the target using a low pH buffer. The screening is repeated several times with increasingly stringent binding conditions of increased Tween concentration until a homologous binding motif emerges. The resulting amino acid sequence constitutes the receptor which is then created using solid-phase peptide synthesis. Using standard Fmoc chemistry, a C terminal cysteine is linked with a 6-mer of poly (ethylene glycol) followed by the identified DNT receptor motif. The C terminal cysteine provides the thiolated end-group for attachment to the gold coated membrane while the poly (ethylene glycol) is incorporated to reduce the response of the system to humidity changes. This DNT binding peptide/ PEG fused polymer will be utilized as the receptive layer for our micromembrane system.

Having identified the specific recognition motif among billions of peptide candidates, the resulting identified peptide receptors were compared, Fig 2., based on the number of phage remaining bound to the target after rigorous washing given a known initial amount of phage. The resultant best binding receptor for DNT was compared against a similar substrate of TNT which differs in the addition of only one nitro group. Fig. 3 shows the panning experiment results, which reveal the selectivity of the peptide sequence for DNT over that of the TNT target. Comparative binding assay data suggests levels of binding to DNT for the TNT designed peptide are on the order of non-specific interaction confirming that the designed peptide is indeed selective for the TNT target.

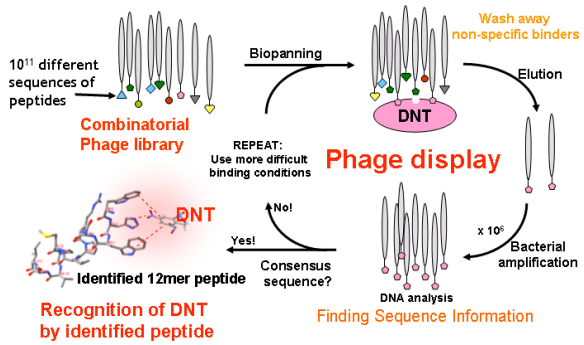

Figure 1. Overview of phage display procedure for DNT receptor screening.

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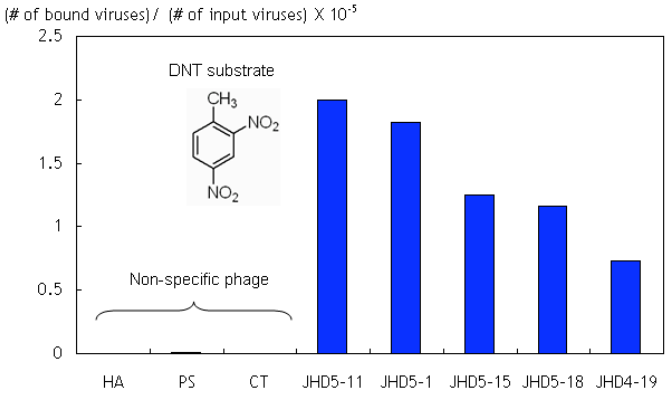


Figure 2. Comparative panning experiment of various phage samples against a DNT substrate where HA, PS, and CT are random phage samples.

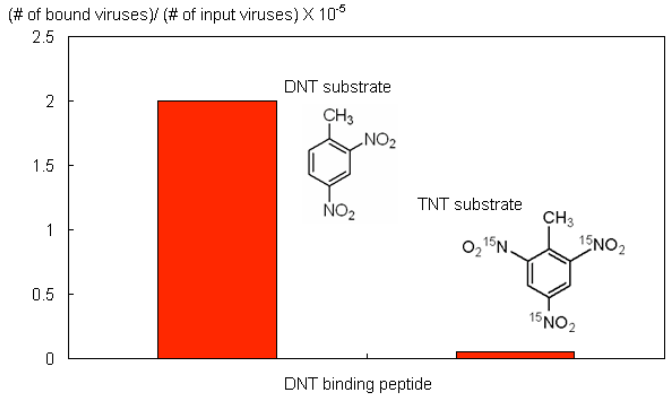


Figure 3. Selectivity experiment of sample JHD5-11 panned against DNT as well as TNT targets.

III. MICROMEMBRANE SENSOR

Fig. 4 shows the operation principle of micromembrane surface stress sensor. The molecular interaction between probe molecules and target molecules generate a surface stress on the thin gold layer. This surface stress causes the structural deflection of the membrane, which generates the capacitance change in electrical sensing. For the fabricated membrane capacitive surface stress sensor as shown in Fig. 5, preliminary chemical responses to water and isopropyl alcohol vapors were measured using a controlled chemical vapor generation system [Fig. 6 (a)] and overall measurement system consisting of a function generator, a lock-in amplifier, a multiplexer, etc [Fig. 6 (b)]. Fig. 7 shows the preliminary measurement results for various water and isopropyl alcohol vapor concentration. In this experiment, simple alkane thiols having different functional end groups [SH-$(CH_2)_{10}$-COOH and SH-$(CH_2)_{11}$-NH_2] were used for probing molecules. Based on the signal to noise ratio of the capacitance change measurement, the developed membrane sensor platform is promising for low concentration chemical vapor detection [5].

Since the thermal strain mismatch between membrane and the thin film coating materials can generate undesired structural deformation for thermal environment change, we proposed a novel temperature compensation sensor design [Fig. 8 (a)]. The proposed compensated design has another gold film coating layer on the bottom of the parylene membrane structural layer. By adding another gold film layer on the bottom of the parylene structural layer, the thermal strain mismatch of the upper part is compensated by that of the lower part. This unique design can also compensate the unwanted signal from the volume expansion mismatch due to the chemical absorption into the parylene layer. As shown in Fig. 8 (b), the compensated membrane sensor has been fabricated using surface micromachining technique and it is under testing now.

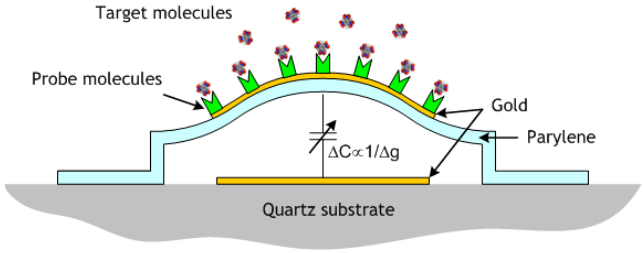


Figure 4. Operation mechanism of micromembrane surface stress sensor

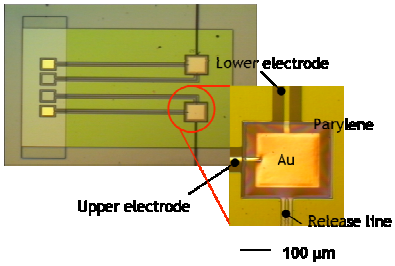
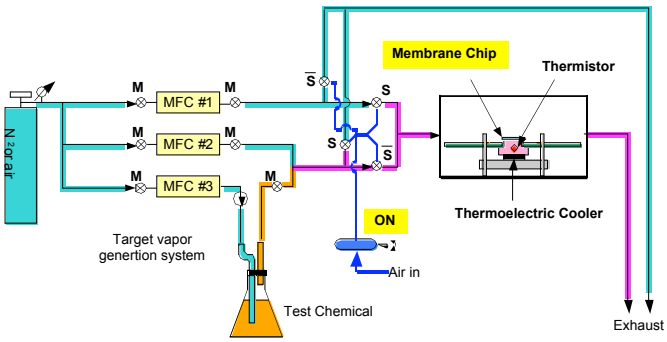


Figure 5. Microfabricated parylene membrane sensor [4].

(a)



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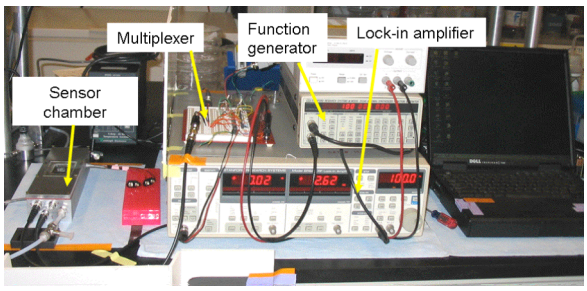
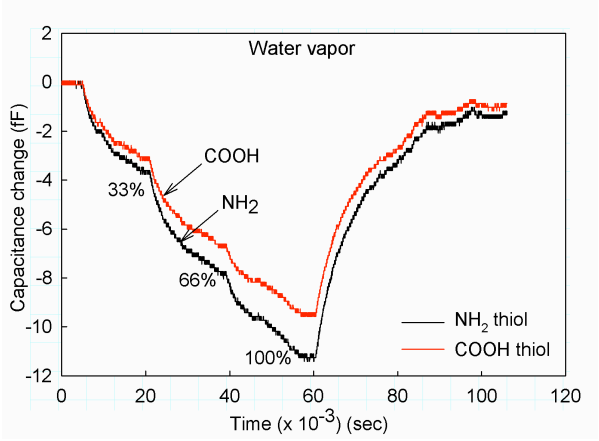


Figure 6. Overall experimental setup. (a) Chemical vapor generation system. (b) Measurement setup.

(a)



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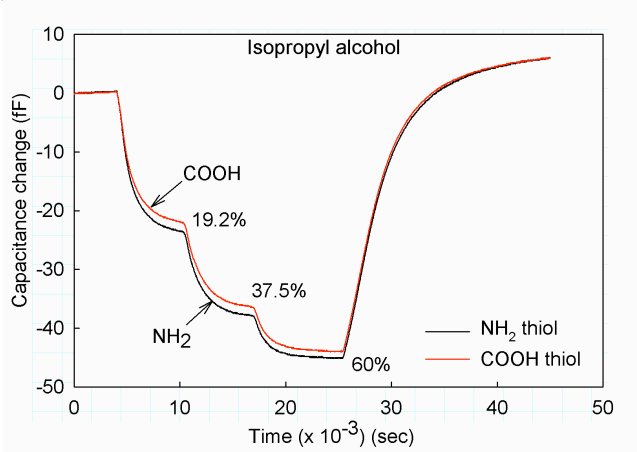
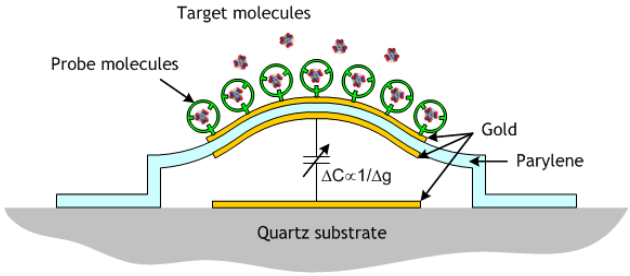


Figure 7. Preliminary experiment for water and isopropyl alcohol vapors. (a) Water vapor. (b) Isopropyl alcohol.

(a)



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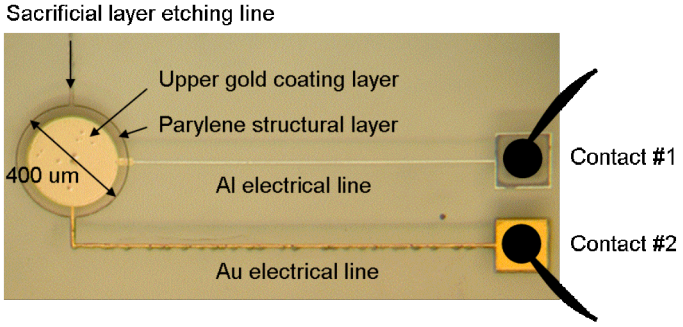
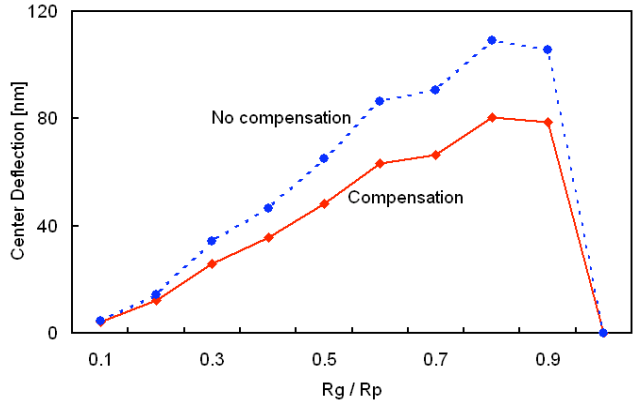


Figure 8. Modified parylene micromembrane surface stress sensor. (a) Operation principle. (b) Fabricated membrane sensor.

Fig. 9 shows the performance simulation result using ANSYS. Fig. 9 (a) shows the center deflections of un-compensated design and compensated design for various gold layer radii, R_g. In this simulation, parylene layer radius, R_p = 200 m, parylene layer thickness, t_p = 0.5 m, and gold layer thickness, t_g = 30 nm, were used. Also, the surface stress change, $\Delta\sigma$ = 10 mJ/m^2 was applied to the thin gold layer. As shown in the figure, the center deflection was maximized in the radius ratio R_g/R_p = 0.8. Also, the center deflection of the compensated membrane was reduced about 27 % due to the increased structural stiffness. However, in the case of the compensated design, the response for unwanted temperature change ΔT = 1 K was decreased about 87 % due to the additional thin gold film layer on the bottom of the parylene structural layer [Fig. 9 (b)]. Although there is some trade-off between sensitivity and temperature compensation, the compensation design has big advantage in power consumption of a portable molecular sensing platform since the design doesn't need to have a temperature controller. It should be noted that conventional bi-material sensing device needs accurate temperature controller, which consumes lots of power, to remove unwanted temperature response.

(a)



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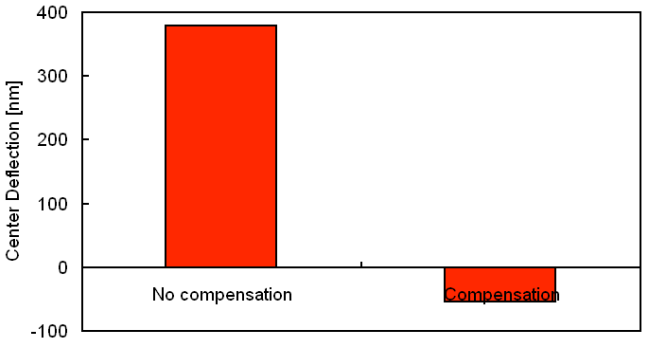
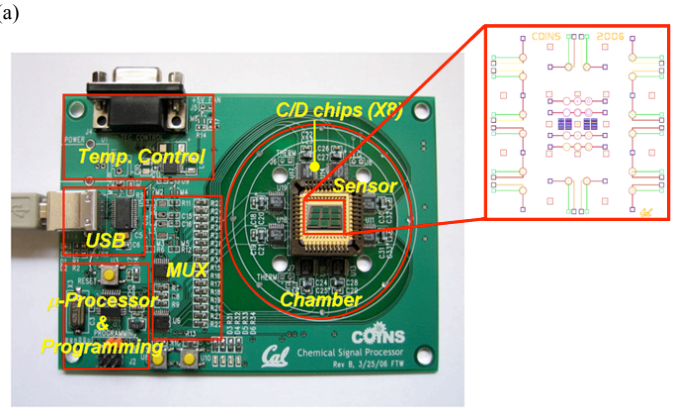


Figure 9. Membrane performance simulation using ANSYS. (a) Membrane center deflection comparison for various gold layer radius, Rg (parylene layer radius, Rp = 200 m, parylene layer thickness, t_p = 0.5 m, gold layer thickness, t_g = 30 nm, surface stress change, $\Delta\sigma$ = 10 mJ/m^2) (b) Membrane center deflection comparison for unwanted temperature variation ΔT = 1 K.

IV. System Integration

For a fully integrated chemical sensing platform, we incorporated the sensing chip and all measurement circuits in a single board. The board includes a fabricated membrane sensor chip, capacitance to digital converter (CDC) chips, microprocessor, USB interface, temperature control, etc. Using the board, sub fF range capacitance measurement, data acquisition speed (for each channel) of 9 samples/sec, and power consumption (for data acquisition) of 17.7 mA @ 5 V could be achieved.

(a)



(b)

Fig. 7. (a) Integrated chemical signal processing board. (b) Portable or field-deployable sensing platform

V. Conclusion and Futrue Work

We found a DNT specific bio receptor using a phage display technique, which will increase the selectivity of the sensor. Also, we have developed a micromembrane sensor and modified the design for undesired temperature and chemical absorption responses. Finally, we built an integrated chemical sensing platform incorporating the sensing chip, the receptor, and the electrical circuits. In the future, we will test the performance of the integrated sensing platform from the point of view of sensitivity and selectivity.

References

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